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Fluid Inclusion Evidence for Ore-Forming Solutions: Phoenixville, Audubon and New Galena Mine Districts, PA

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by

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This manuscript is dedicated to my husband, Frank Lawler, for without his help, my dream may have never become a reality.

ABSTRACT

The Audubon, Phoenixville and New Galena Pb-Zn-Cu vein deposits of southeastern Pennsylvania have been investigated by microthermometric analysis of fluid inclusions in sphalerite, dolomite and quartz. The results obtained from primary and psuedosecondary inclusions in sphalerite indicate that the ore was deposited by a sodium rich brine of moderate salinity (11-14 equivalent wt. % NaCl) at temperatures probably near 200°C. The Na-rich character of the fluid suggests that dissolved constituents in the fluids were derived from Na-rich sedimentary rocks of the Newark basin. Local fluid-wallrock interaction may have produced slightly higher salinity fluids (15-16 equivalent Wt. % NaCl) present at New Galena. The data obtained in this study suggest that igneous activity did not necessarily cause the developement of the ore fluid as mineralogical evidence indicates that temperatures throughout the basin reached 200°C. Deposition of the ore occurred where connate, metal rich brines migrating through faults and fractures encountered temperature and chemical conditions, developed through wall rock interaction with the ore solution, which favored sulfide precipitation.

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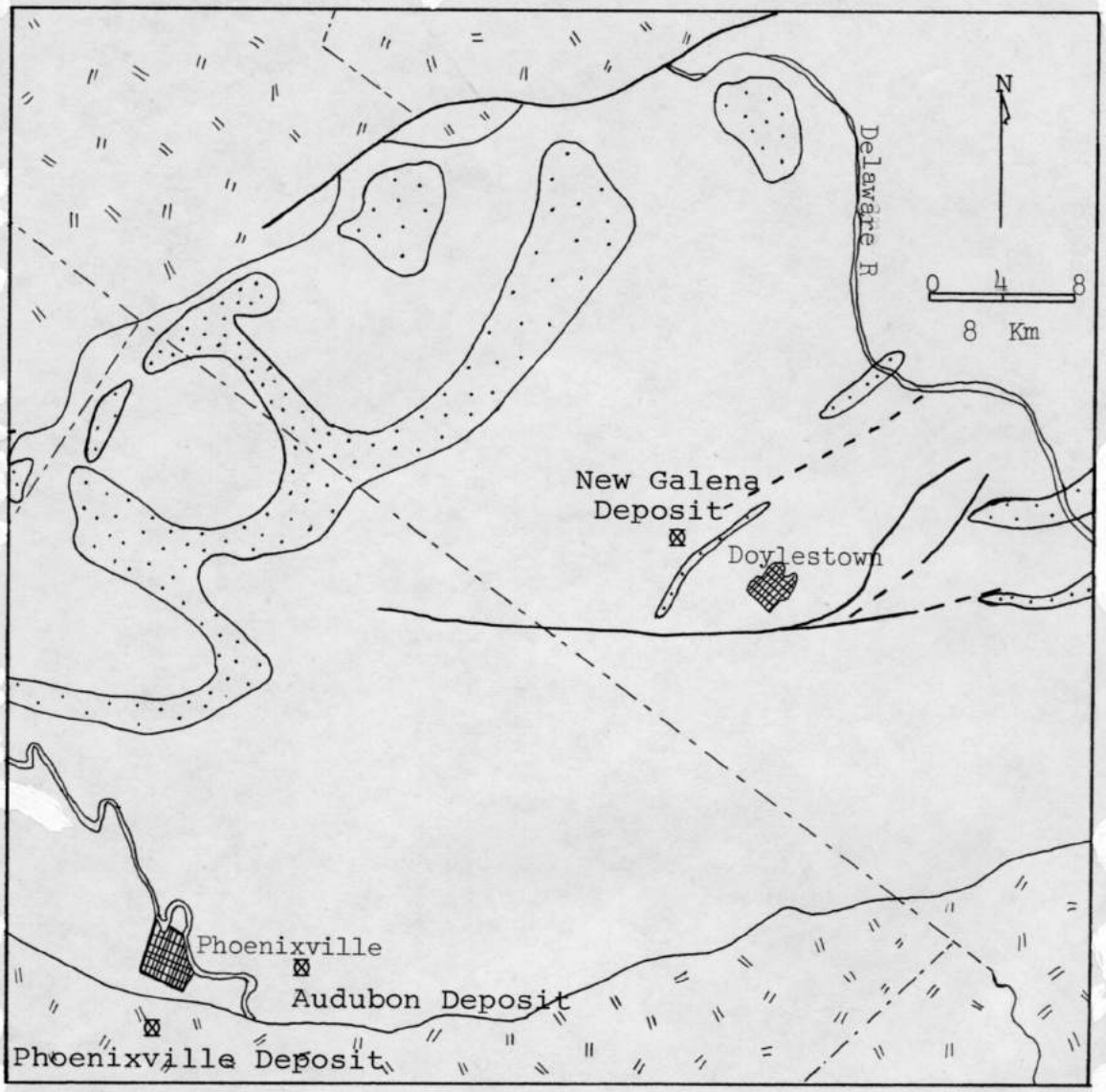
INTRODUCTION

There are approximately 40 Pb and Zn deposits in southeastern Pennsylvania. Most of these are located in the Valley and Ridge or Piedmont province and are hosted by lower Paleozoic carbonate rocks. Three Pb, Zn and Cu deposits occur in and near the Triassic-Jurassic Newark Basin; Phoenixville, Audubon and New Galena mine districts. These three deposits are the focus of this investigation and were selected for fluid inclusion study. All were economically exploited at one time but are no longer actively mined. These deposits were chosen specifically because they are unique to Pennsylvania in that they occur in non-carbonate host rock and because their origin is problematical.

The New Galena and Audubon ores occur in Triassic siltstones and shale of the Newark Basin, but Phoenixville ores extend from Triassic siltstone into Precambrian metamorphic rocks of the Piedmont province south of the basin (Fig. 1). In all cases chalcopyrite, galena and sphalerite occur in northeast trending, steeply dipping veins which occupy faults and fractures. Geologists, for example: Rogers 1858; Miller 1924, have extensively studied these deposits concluding that they formed from



TRIASSIC SEDIMENTS

TRIASSIC DIABASE

PALEOZOIC AND
CRYSTALLINE ROCKS

FAULTS

DEPOSITS

Figure 1. Location Map

hydrothermal solutions derived from igneous intrusions. However, no Triassic age or younger igneous bodies of large size occur near the deposits, so early workers postulated that intrusive rocks at depth must have been the source for the hydrothermal solutions. Later, aeromagnetic surveys (Bromery and Griscom, 1967) showed no significant buried igneous bodies in the Newark Basin. So the origin of the ore remains problematical.

A study of fluids trapped as inclusions in transparent ore and gangue minerals can yield information about ore forming solutions. Fluid inclusion data can be very useful in gaining a more complete understanding of ore deposition (Spooner, 1981). Much fluid inclusion work on ore deposits has concentrated on sphalerite since it is one of the few transparent ore minerals. Studies of fluid inclusions in magmatic vein, Mississippi Valley, Kuroko and porphyry copper deposits have yielded data on temperature, composition and density of ore forming solutions (Roedder, 1977). This study has been designed to provide similar information and should shed some light on how and why this ore was formed.

Sphalerite samples used in this study are large clear, zoned crystals ideally suited for fluid inclusion work. In addition, some inclusions in the common gangue

minerals quartz and carbonate were examined for comparison. Few inclusions in gangue minerals were found to be suitable for study as some quartz and most carbonate was too cloudy and inclusions could not be adequately viewed.

The aim of the study was to determine the nature of the fluids which deposited the lead, zinc, and copper deposits of the Audubon, Phoenixville, and New Galena mine districts. In any fluid inclusion study it is necessary to make certain fundamental assumptions (Roedder, 1972). The first is that most of the inclusions studied are samples of the ore forming fluid. The second, that they have not changed in any major way since the time of entrapment (i e., by necking down, leaking, solid precipitation on the walls of the inclusion and/or stretching). This second assumption must be examined with care as sample preparation and even microthermometric techniques can affect its validity, as will be demonstrated below.

REGIONAL SETTING

In late Triassic time, eastern N. America was subjected to tensional stress caused by incipient rifting of Laurasia to open the modern Atlantic Ocean. This resulted in the development of northeast trending fault grabens, in which non-marine sediment accumulated (Van Houten, 1977). One of these, the Newark Basin trends generally northeast and stretches 224 km from southeastern New York State through central New Jersey and adjacent Pennsylvania. The late Triassic-early Jurassic Newark Group of the Newark Basin, consists of 4880 to 6100 m of non-marine sedimentary rocks and associated mafic intrusive and extrusive igneous rocks. The Newark Group is relatively sodium rich, possibly due to detritus originating from sodium-rich crystalline rocks to the southeast (Glaeser, 1966). The basin fill appears to thicken to the northwest where it is terminated by northeast trending border faults (Van Houten, 1969). The southeast margin is obscured by onlapping Cretaceous rocks, but geologists believe that this margin is also faulted (Cloos and Pettijohn, 1974). The original extent of the basin fill is thought to be only slightly larger then the present outcrop margin (Glaeser, 1966). Northeast trending faults and systematic fracture sets, related to rifting, disrupt the thick section of Newark sediments.

The oldest member of the Newark Group is the Stockton Formation, a fluvial deposit consisting of interbedded red sandstone, siltstone, conglomerate and shale. Bascom and Stose (1938) estimated that the Stockton is approximately 1000 meters thick at the southeastern margin where both the Phoenixville and Aububon deposits occur. Above the Stockton in the central portion of the basin, the Lockatong Formation, a large lacustrine lens, was deposited. It consists of 1150 meters of gray dolomitic and pyritic shale interbedded with analcime-rich argillite. The Lockatong grades upwards and interfingers with the Brunswick Formation, another fluvial deposit, comprising a succession of reddish-brown sandstone and siltstone. The Brunswick is 3000 meters thick in the central portion of the basin, but thickens to the southeast and west as the Lockatong pinches out (Van Houten, 1969).

Basaltic magma intruded the lithified sediments of the Newark Basin in Pennsylvania in early Jurassic time, forming thick diabase sheets and dikes (Hotz, 1952). Some investigators suggested this igneous activity caused the deposition of the sphalerite, chalcopyrite and galena ores in or near the Newark Basin, at Audubon, Phoenixville and New Galena (Bascom and Stose, 1938). It is apparent, however, that a close spatial relationship between ore

and diabase does not exist (Smith, 1977). The closest intrusive body of any magnitude to any of these deposits lies 10 km from New Galena (Fig. 1).

After most igneous activity and filling of the basin was complete, an episode of faulting, rifting, and warping occurred along the entire basin. Transverse extensional fractures and dikes cut across the disrupted basins (Van Houten, 1977).

GEOLOGIC SETTING OF DEPOSITS

A comprehensive report on the lead-zinc deposits of Pennsylvania (Smith, 1977) describes in detail most of the known geological relations of these deposits. The report is quoted extensively as most of the geology is now obscured by urbanization.

The Audubon district, which includes the Perkiomen, Whim shaft, and Ecton mines, is located about 8 km east of Phoenixville, Pennsylvania in Montgomery County (Fig. 1). The district was mined for copper until the 1860's after which the ore became too sparse and irregular to be profitable. The ore occurs along a steeply dipping mineralized fault which trends N27°E to N35°E. The strike of the fault is roughly parallel to northeast trending border faults which bound the northwest margin of the basin. The most abundant ore mineral is chalcopyrite, generally accompanied by lesser amounts of galena and sphalerite. The gangue consists mostly of quartz with some ferroan dolomite. The surrounding Stockton siltstone is bleached and altered at the contact with the ore zone. The ore zone is reportedly 15 to 25 feet wide according to five exploratory drill holes logged by the United States Bureau of mines in 1950 (Earl, 1950). The ore in the upper levels is oxidized

to a depth of about 250 feet. Secondary minerals include cerussite, anglesite, azurite, malachite, chrysocolla, smithsonite, and pyromorphite.

The Phoenixville deposits are located approximately 3 km south of Phoenixville in Chester County (Fig. 1). Lead mining began in 1808 climaxed from 1851 to 1855 and then gradually declined until 1870 when all mines became idle. One small mine operated from 1917 to 1920. In a recent U.S. Bureau of Mines investigations, eight diamond drill cores were logged to try and locate the veins beneath old mine workings, but no significant mineralization was found (Reed, 1949). Smith (1977) suggests that the drill holes may have been improperly located and the veins do continue at depth.

The area north of the ore district is underlain by the red siltstone of the Stockton formation. South and west of the Triassic rocks are various Precambrian igneous and Paleozoic metamorphic rock units (Bascom and Stose, 1938). The ore occurs in quartz veins which were emplaced along northeast trending near vertical faults and fractures, which extend from Precambrian rocks into the Stockton siltstone defining a Triassic or younger age to the mineralization. The faults are parallel to the regional systematic fracture set which trends N35°E and N55°E (Harms et al., 1979). Reed (1949)

claims that small Triassic diabase dikes intruded into other fractures in the ore district and that three small dikes are cut by the Wheatly vein (Miller, 1924).

Major veins are 2½ to 5 feet wide and contain abundant sphalerite, argentiferous galena, and/or subordinate chalcopyrite and pyrite. The oxidized ore zone extends down at least 250 feet and is primarily pyromorphite, with smaller amounts of cerussite, malachite and anglesite.

The Phoenixville district contains a number of formerly productive deposits in Precambrian gneiss. Samples used in this study are from the Brookdale, Montgomery County, Chester County, S.W. Chester County mines, and also 130 m southwest of S.W. Chester County mine. The host rock is described by Bascom and Stose (1938) as granodiorite, a medium grained, quartz, feldspar, mica rock with accessory magnetite, ilmenite, apatite, titanite, zircon and pyrite. Rogers (1858) reports that the host rock is extensively altered near the contact with the mineralized veins. Smith (1977) describes the host rock as a "granitic gneiss" because of its metamorphic foliations.

The New Galena mine area is in Bucks County, 16 km northwest of Doylestown, Pennsylvania (Fig. 1).

Extensive open pit mining began in 1861 and continued until the 1920's. The Bureau of Mines drilled two holes to investigate the potential downward extension of the ore, but little ore was observed. The pits are presently inaccessible as they are filled with water.

The country rock in the vicinity of the mine at New Galena consists of Triassic dark gray dolomitic and pyritic shales of the Lockatong Formation. A small diabase sill crops out 300 m south of the main pit and Miller (1924) states that diabase was found on the dump, but the Bureau of Mines drill holes did not cut diabase.

The ore is confined to shattered brecciated zones and both replaces and fills void space in the host rock. The wallrock sometimes appears altered. The mineralized vein is over 410 m long, trends N45°E which is roughly parallel to regional faulting, and dips steeply to the southeast. The ore is a coarse grained aggregate of galena, sphalerite and fragments of country rock with ferroan dolomite as the common gangue mineral. Minor associated minerals include pyrite, chalcopyrite, ankerite, pyromorphite and cerussite. Smith (1977) states that ore deposition was controlled by the presence of a permeable breccia, with replaceable dolomite in a reduced pyritic host probably containing acid-soluble carbonate.

Description of Samples

Fourteen hand specimen sized samples were supplied by Dr. R.C. Smith II of the Pennsylvania Geological Survey, for the study. Sphalerite rich samples were purposely chosen because of the nature of the study, (i.e.) to facilitate fluid inclusion work. Therefore, the samples described are not necessarily representative of the mineralogy of the deposits but rather reflect the necessity of transparent minerals for fluid inclusion study.

Four samples are from the New Galena mine dumps and are made up largely of golden brown sphalerite with small amounts of galena in brecciated Lockatong shale. The sphalerite and galena are accompanied by small amounts of quartz and ferroan dolomite gangue and trace amounts of chalcopyrite and pyrite. In one case, the gangue minerals appear to be earlier than sphalerite and galena because a fracture filled with dolomite and quartz is visibly offset by a sphalerite-galena rich vein. In another sample the Lockatong shale is apparently altered as it is light brown. These samples show evidence that ore has replaced fragments of dolomitic Lockatong shale.

Four samples are from the Audubon district ; two from

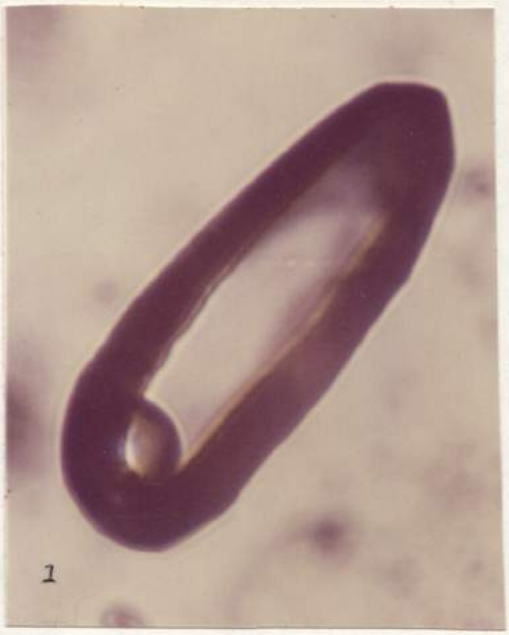
the Ecton mine dumps, one from inside the Ecton mine and one from the Whim shaft dumps of the Perkiomen mine. The Ecton mine samples are brown sphalerite with both clear and white quartz. Quartz appears to be an early mineral as euhedral crystal faces project into massive sphalerite and galena. One sample contained a small amount of chalcopyrite. The sample from the Whim shaft consists of major sphalerite and lesser galena and chalcopyrite with chlorite gangue.

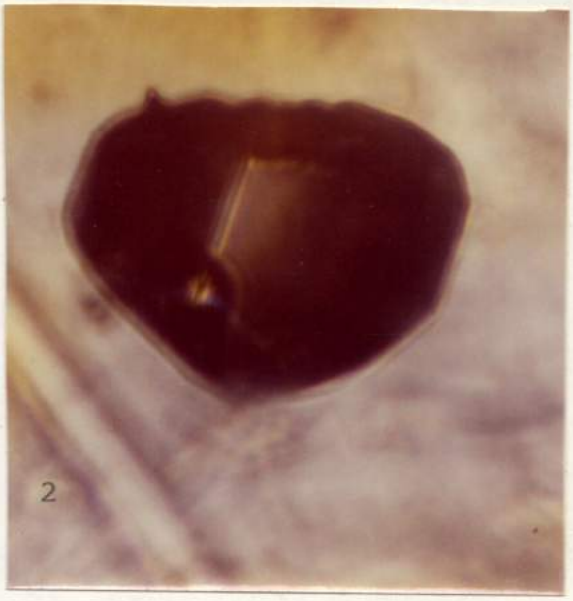
Six samples from Phoenixville show a varied mineralogy. Two samples from the Montgomery County mine dumps are golden brown sphalerite in clear and white crystalline quartz with small amounts of galena and chalcopyrite. Samples from the SW Chester County mine dumps and 130 m southwest of the aforementioned mine are similar in that both are golden brown sphalerite with quartz, ferroan dolomite, and calcite gangue but the former contains some chalcopyrite. A sample from the Brookdale mine is mainly dark brown sphalerite with small amounts of quartz and ferroan dolomite gangue and a trace of chalcopyrite. The Chester County mine sample is dark brown sphalerite in cherty quartz with a trace of chalcopyrite. In all these samples the gangue minerals also seem to be earlier than ore but chalcopyrite may occur early with quartz.

EXPERIMENTAL TECHNIQUE AND ASSUMPTIONS

One doubly polished thick section (.5 to 1 mm thick) was prepared from each sample. Fluid inclusions in yellow, gold and orange sphalerite, clear quartz, and ferroan dolomite, were studied in small unmounted chips from the polished sections. The inclusions in this study are, without exception, two phase (liquid + vapor) aqueous inclusions. They range in size from 101 to .1 mm in length and include irregular, elongate and negative crystal shapes (Plate 1). The fluid inclusions were examined microthermometrically between -150°C and +225°C with the aid of a Chaix Meca heating and freezing stage (Poty et al., 1976). The cooling-heating stage is calibrated by observing melting points of compounds of known melting temperature. (Fig. 2)

The technique involves freezing the inclusions and then heating them at a very slow rate (0.5°/min) and observing the phase changes which occur. The phase changes observed provide information on composition, density, and temperature of trapping of the fluids, by comparison with known experimental phase data. Freezing point depression of ice (Tm) provides an estimate of total salinity (Potter et. al., 1978) and other observed phase changes further characterize the composition of the fluids.





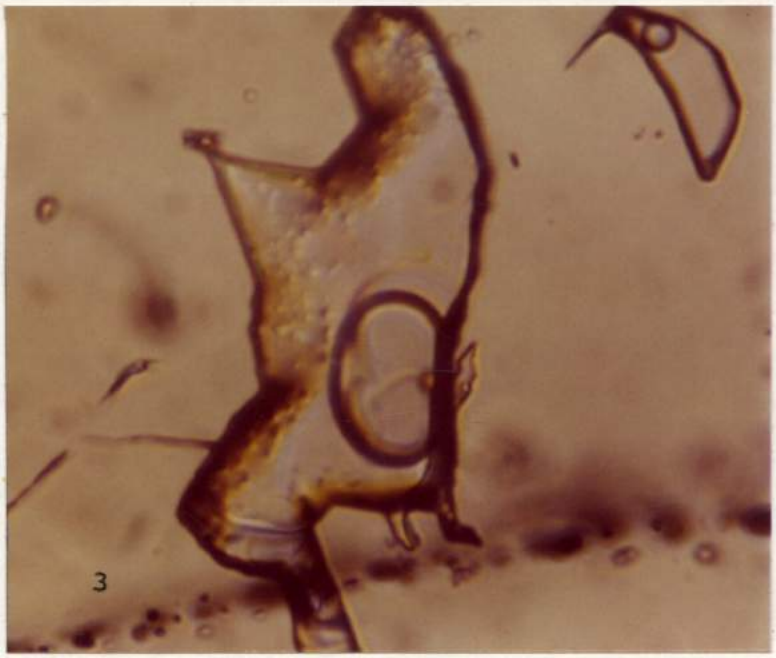


Plate 1

Figure 1. Elongate fluid inclusion in sphalerite.
Figure 2. Negative crystal fluid inclusion in sphalerite.
Figure 3. Irregular fluid inclusion in sphalerite

Fluid Inclusions are magnified 500x.

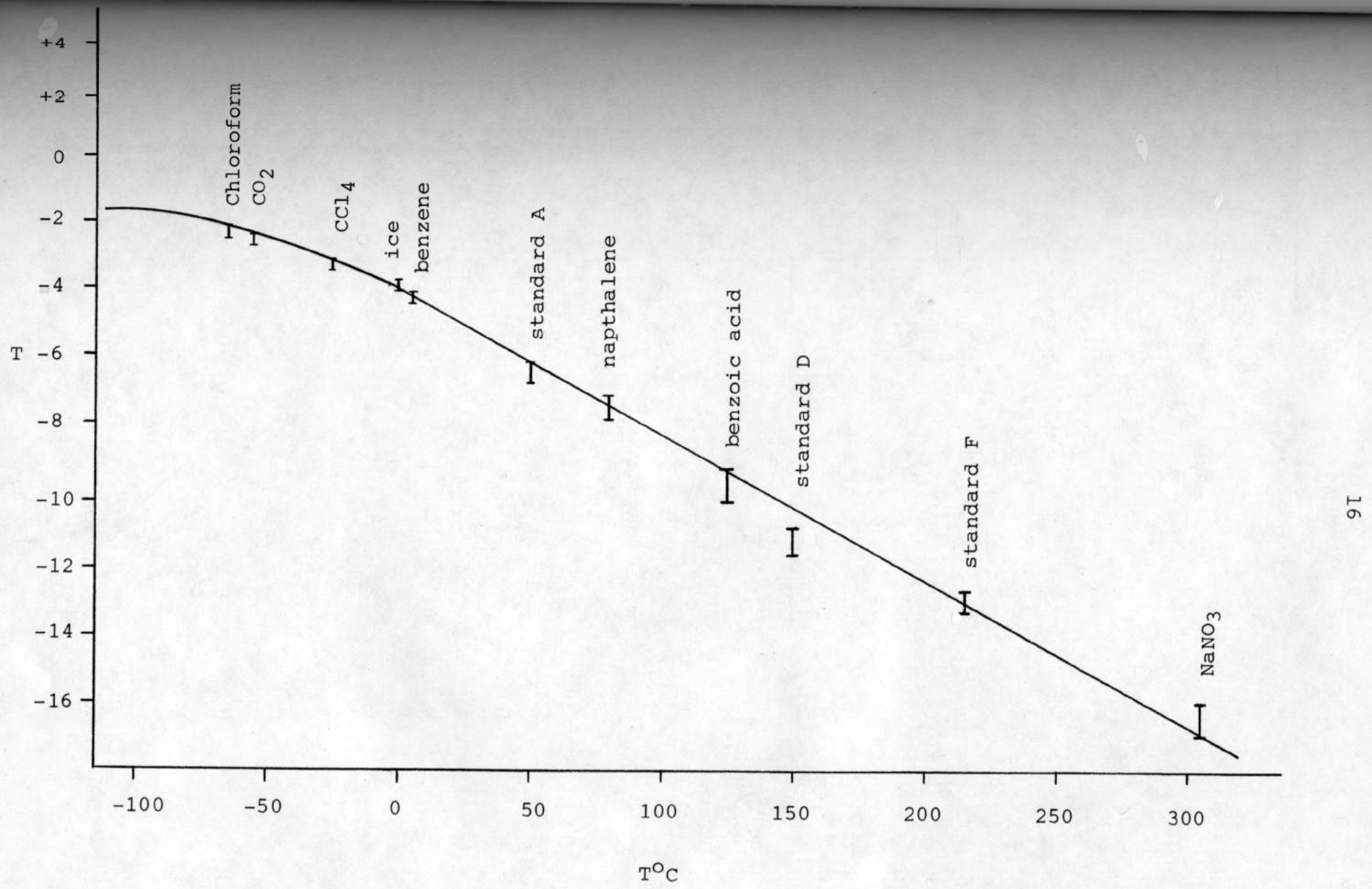


Figure 2. Temperature calibration curve for heating/cooling stage. T=Tactual-Tobserved

The depression of the freezing point of ice in the system $NaCl-H_2O$ is a measure of its salinity and thus permits an estimation of the NaCl concentration in the fluid. Although most fluid inclusions contain ions other than Na, such as K, Ca, and SO_4, Potter and Haas (1977) have shown that many solutions present in natural fluid inclusions have similar freezing point depressions.

Homogenization of the liquid and vapor inclusions by heating provides an estimate of the density of the fluid which, along with composition and estimated pressure conditions for entrapment, provides the temperature of formation for the fluid (Potter, 1977). The temperature of homogenization (Th) can be obtained with reasonable accuracy using the heating stage. The accuracy is related to both the precision of the equipment and to the optics of the inclusions. Roedder (1976) discusses various heating stages and problems associated with equipment and methods. The errors introduced by heating methods are small when compared to possible errors in independent pressure estimates.

LOW TEMPERATURE PHASE CHANGES

Various phase changes were observed during low temperature runs on these inclusions. The fluid in the inclusions usually freeze between -40° and -60°C; the freezing is detected by contraction of the vapor bubble. In some inclusions, the vapor bubble completely disappears upon freezing. Immediately upon freezing the fluid, fine crystals begin to form. These fine crystals are most easily seen in larger inclusions. Further cooling to -100°C causes little change in the appearance of the inclusions except that the vapor bubble outline sometimes becomes masked by darkening and coarsening of the finely crystalline mass.

Upon warming from -100°C, phase changes usually begin to be observed between -55° and -45°C but occassionally can be seen as low as -60°C. These changes, interpreted as first melting, are represented by slight lightening in the area of the contracted vapor bubble and/or coarsening of the fine crystals formed upon freezing. Sometimes, the whole inclusion gets extremely dark and the bubble becomes invisible.

Continued warming causes gradual coarsening of the crystals and sharp crystal edges usually become rounded by -30°C. At this time, a liquid phase becomes evident.

At approximately -25°C, melting becomes more rapid and one of the solid phases always melts by -21°C. When this phase melts, the vapor bubble usually pops out and rounded ice crystals remain. The ice crystals gradually get smaller and disappear as warming proceeds until all ice is eventually melted between -12 and 7°C.

Variations on this progressive melting sequence are s ometimes seen. Occasionally, a liquid phase will be obvious at lower temperatures, i.e. -40°C. In these same inclusions, a phase may melt between -35°C and -30°C, but the rest of the melting path progresses as before. Another variation in melting behavior is seen. In the few inclusions which usually freezeby -40°C freezing is accompanied by disappearance of vapor phase. A small amount of melt is visible around -21°C and the ice melts usually between -3 and -1°C. Often, the vapor bubble does not return until +9°C, long after the ice melts.

HIGH TEMPERATURE PHASE CHANGES

Phase changes observed during high temperature runs are fairly simple. Most often, the vapor bubble gradually shrinks upon heating until it eventually disappears and a homogeneous fluid results. In high relief inclusions this phase change can be hard to observe because the shrinking vapor bubble adheres to the wall of the inclusion and is hidden in the dark zone of total reflection formed along that wall. In some small inclusions, vapor disappearance is quite obvious as the vapor bubble begins to vibrate back and forth upon heating. This movement ceases upon homogenization to the liquid phase, thus homogenization is easily seen.

MICROTHERMOMETRY RESULTS

All reported temperatures have been corrected according to the calibration curve. (Fig. 2).

Measurements were made on 25 aqueous inclusions in sphalerite from the New Galena ore. (Appendix A). The liquid + vapor inclusions were found to show a bimodal distribution of final melting temperatures of -8^{o} and $-11^{o}C$ which correspond to 11 and 15-16 equivalent wt. % NaCl, respectively (Fig. 3). Temperatures of first observed melting were occasionally as low as $-60^{o}C$ but most commonly were between -45^{o} and $-55^{o}C$. One other phase, probably hydrohalite ($NaCl \cdot 2H_2O$) melted between -20.3^{o} and $-22.8^{o}C$.

A small number of aqueous inclusions with lower salinities were observed. The ice in these often melted before any vapor phase reappeared so it was impossible to accurately determine their salinity. This is because melting is occurring along a divariant (liquid-solid) curve rather than at an invariant (liquid-solid-vapor) point. Even so, salinity is probably low because there is very little observable melting other than the ice phase. The melting temperature of ice in these inclusions lies in the range -5.7^{o} to $-.5^{o}C$ equivalent to 1 to 8 weight % NaCl.

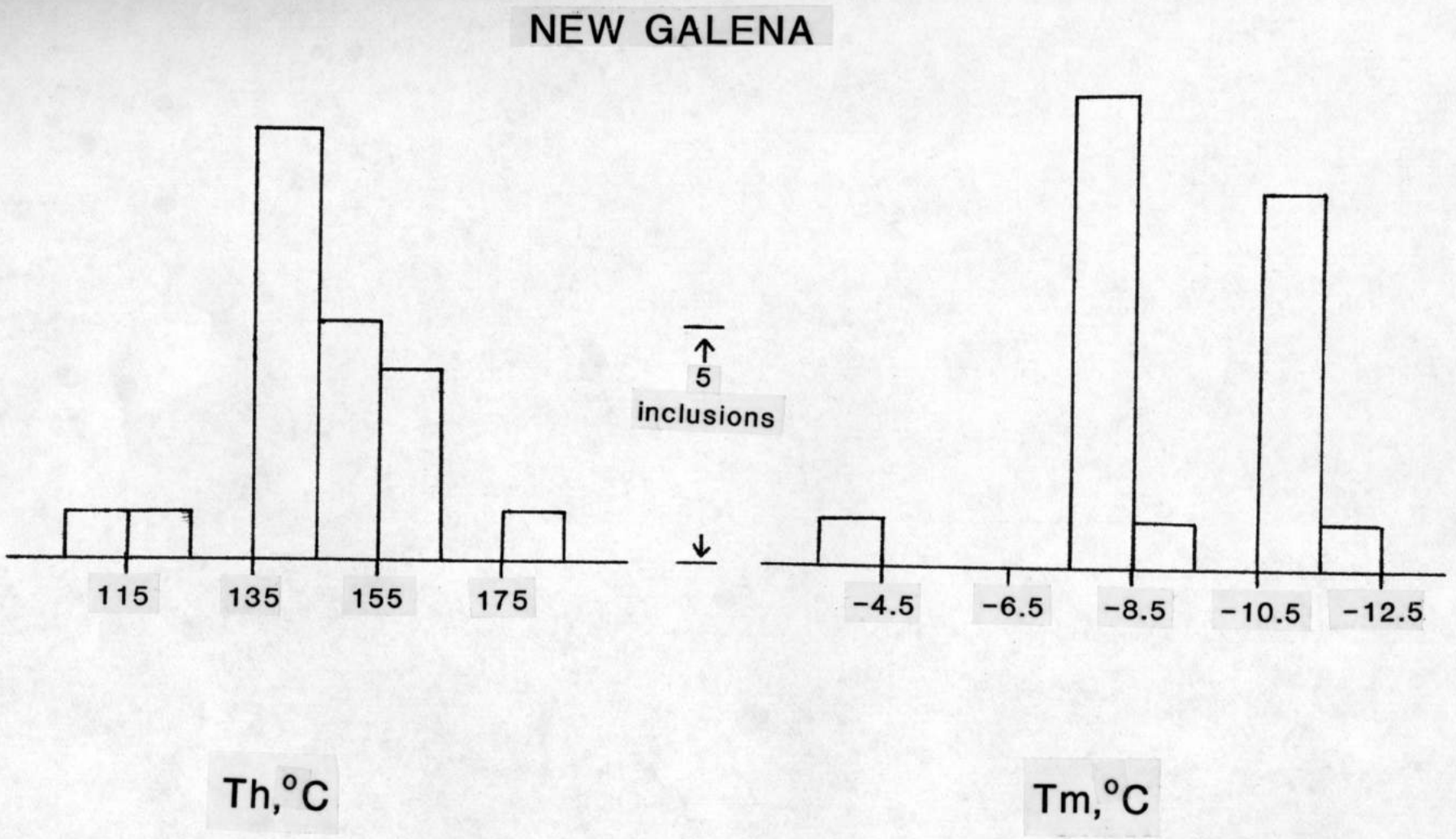


Figure 3. Frequency distribution histograms for homogenization temperatures (Th) and melting temperatures of ice (Tm) for inclusions in New Galena ore.

All of the moderately saline inclusions homogenize between 135° and 180°C but the majority have Th in the range 135° and 155°C (Fig. 3). The low salinity inclusions homogenize between 110° and 115°C.

One inclusion in ferroan dolomite showed first observed melting at -52° and a final melting temperature of -9.2°C which is equivalent to 13 wt. % NaCl. It homogenized at -171.6°C.

Audubon

Measurements were made on 40 aqueous, two-phase inclusions in sphalerite and quartz (Appendix B). Final melting temperature of ice in inclusions in sphalerite ranged from -6.5° to -9.6°C but a majority have melting temperatures between -8.5° and -9.5°C which corresponds to 12 to 13 equivalent wt. % NaCl (Fig.4) First observed melting was commonly between -50°C and -60°C and the NaCl dihydrate melts in the range -21.4° to 22.9°C. A phase disappearance was sometimes visible around -35°C.

Low salinity inclusions also occurred in these samples. In a few of these, ice melted in the presence of a vapor phase at temperatures between -2.8° and -4.6°C indicating salinities of 5-7 wt. % NaCl. Sometimes, the ice melted before the vapor phase reappeared at +3°C.

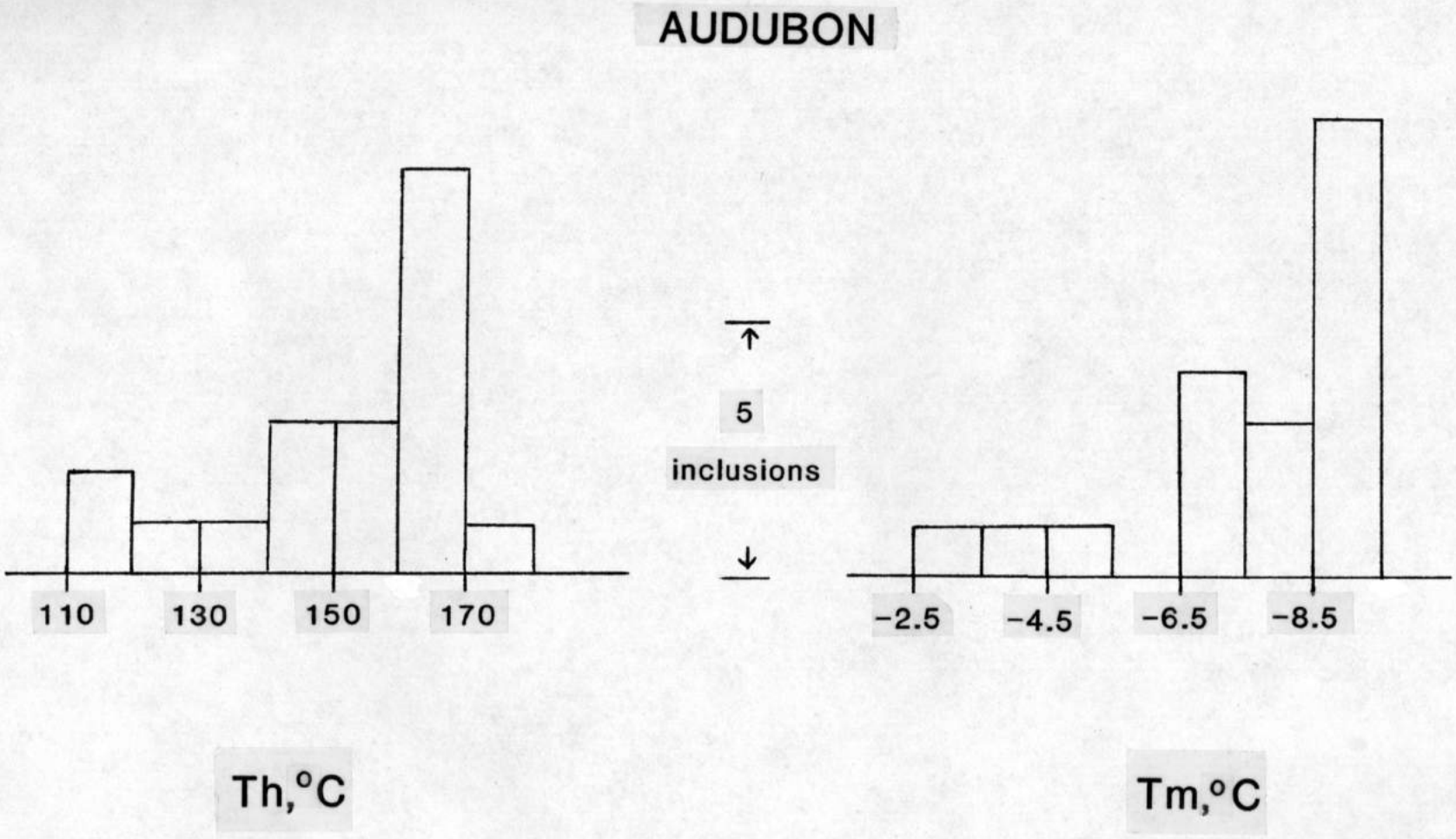


Figure 4. Frequency distribution histograms for homogenization temperature (Th) and melting temperature of ice (Tm) for inclusions in sphalerite from Audubon.

First melting was usually not seen but occasionally a phase would apparently disappear around -21°C.

Inclusions in quartz had final melting temperatures mostly between -7 to -9° corresponding to 11 to 13 equivalent wt. % NaCl, (Fig. 5). First melting is mainly detected between -50° and -60°C and a phase disappearance, presumably hydrohalite occurs between -26° and -22°C.

Homogenization temperatures for moderate salinity inclusions in sphalerite ranged from 137° to 174°C (Fig. 4). Those with higher salinity generally homogenize at the upper end of the temperature range. Low salinity inclusions, when not affected by stretching (see below), homogenize between 110° and 120°C. Inclusions in quartz have Th_1 which ranges between 100° and 210°C (fig. 5).

Phoenixville

Most of the 17 inclusions studied in Phoenixville sphalerite samples have final melting temperatures in the range -7 to -10°C which corresponds to 11 to 14 equivalent wt.% NaCl (Appendix C). The distribution is somewhat bimodal (Fig. 6). Melting was generally detected by -50°C but some were as low as -57°C. The hydrohalite phase always melted between -21.4° and -24.9°C. Low salinity inclusions have melting temperatures of ice in the presence of vapor between -2.8 and -5.1 which is

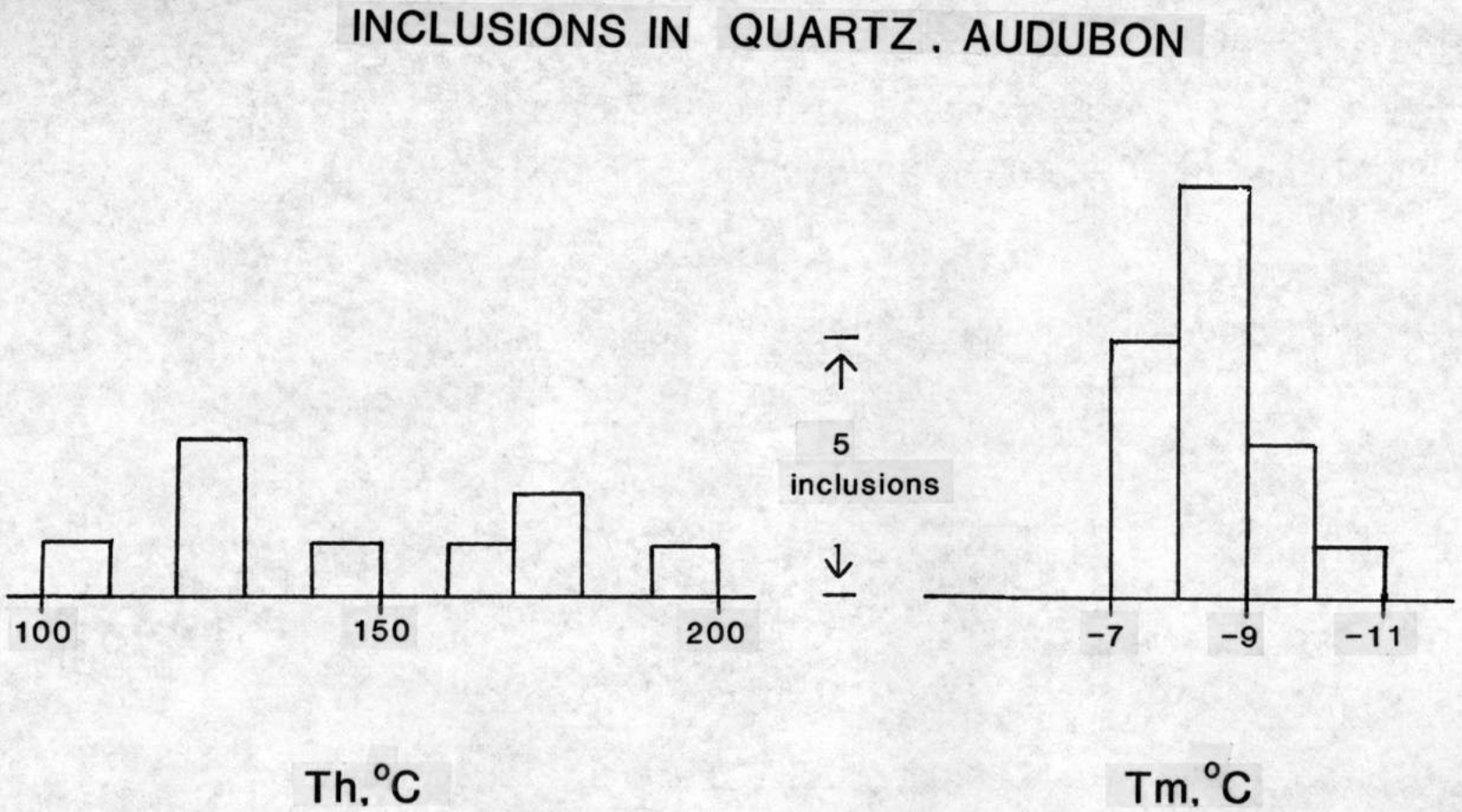


Figure 5. Frequency distribution histograms for homogenization temperature (Th) and melting temperature of ice (Tm) for inclusions in quartz from Audubon.

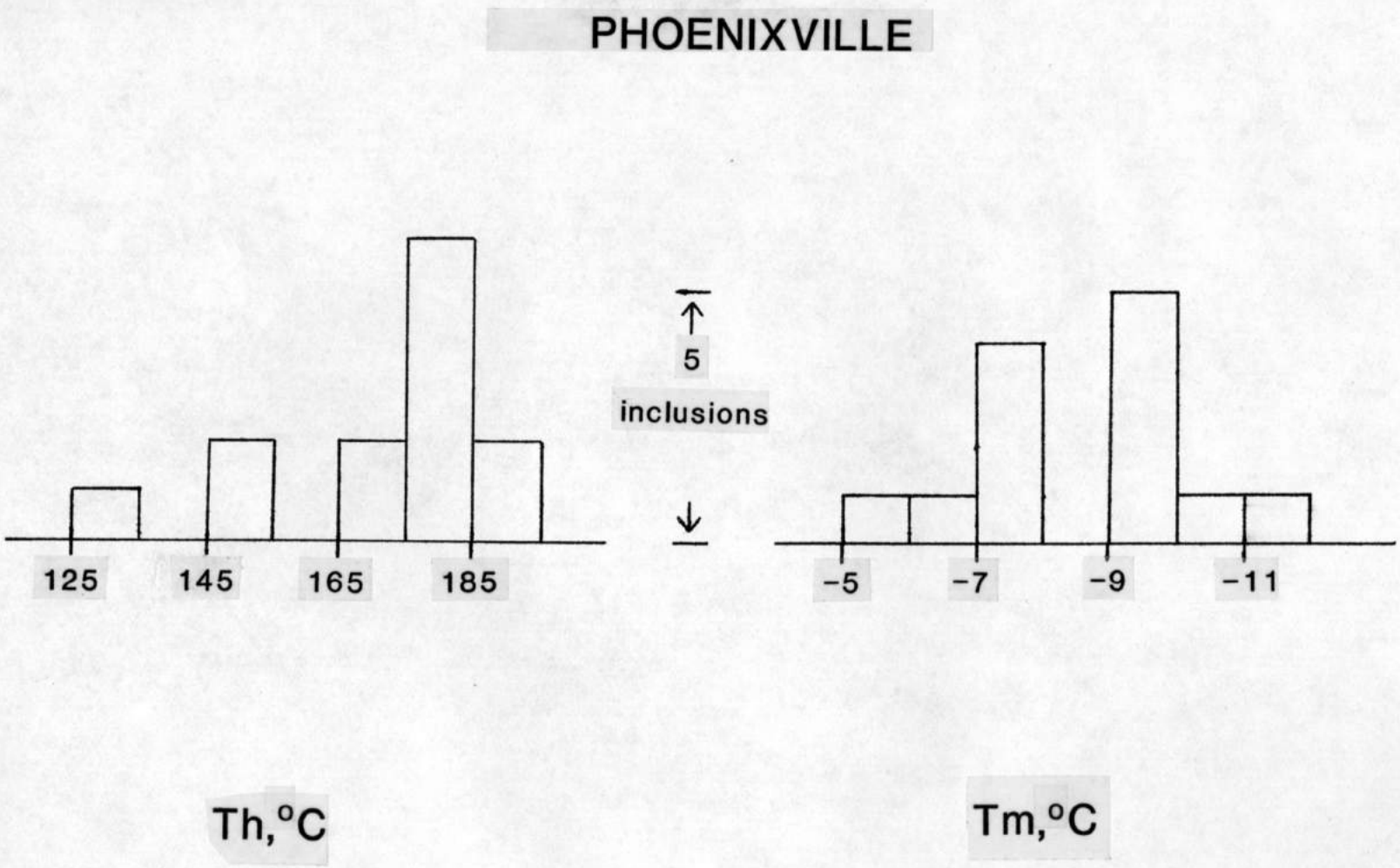


Figure 6. Frequency distribution histograms for homogenization temperature (Th) and melting temperature of ice (Tm) for inclusions from Phoenixville sphalerite samples.

equivalent to 3 to 7 wt. % equivalent NaCl.

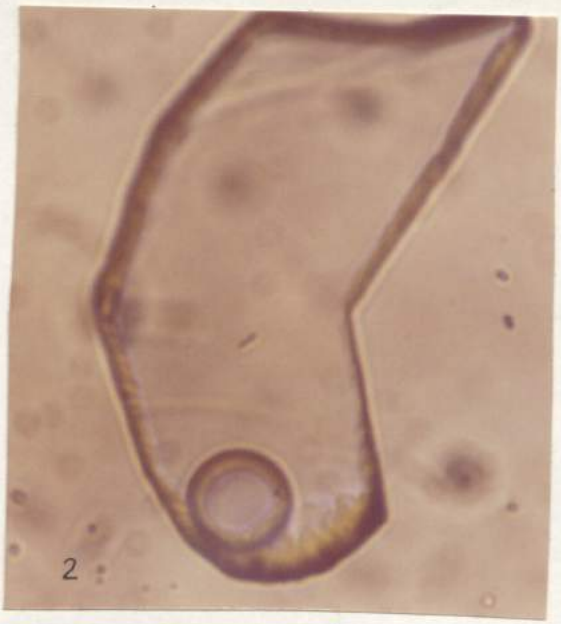
Most inclusions homogenize between 175° and 187°C but Th as low as 130° was observed for the 10 wt. % NaCl inclusions. Low salinity inclusions had been frozen before they were heated, so were probably affected by stretching (see below).

One inclusion in ferroan dolomite was measured and had a final melting temperature of -9.9° suggesting a salinity of 13-14 wt. % NaCl. The inclusion homogenized at 177.1 C.

QUALITATIVE OBSERVATIONS

The nature of the inclusions studied must also be considered in order to characterize the ore forming solutions. Primary inclusions are formed during crystal growth, and usually are large and randomly oriented. Secondary inclusions are fluids trapped at some later time and are most often small numerous inclusions localized along healed fractures. Pseudosecondary inclusions are also found along healed fractures but the healed fractures presumably formed while the crystal was growing (Roedder, 1972). Thus, primary, pseudosecondary, and secondary inclusions in sphalerite need to be distinguished in order to determine the nature of the ore-forming solution.

Freezing data collected from these samples indicate there are at least two fluids present in the sphalerite crystals. The moderately saline brine is thought to represent the primary ore forming solution because moderate salinity inclusions are usually large, isolated and ubiquitous (Plate 2). Low salinity inclusions are more likely secondary or pseudosecondary as they always occur in groups, are small, and mainly occur along healed cracks or cleavage planes (Plate 2). However, some inclusions may be pseudosecondary as they are thin,



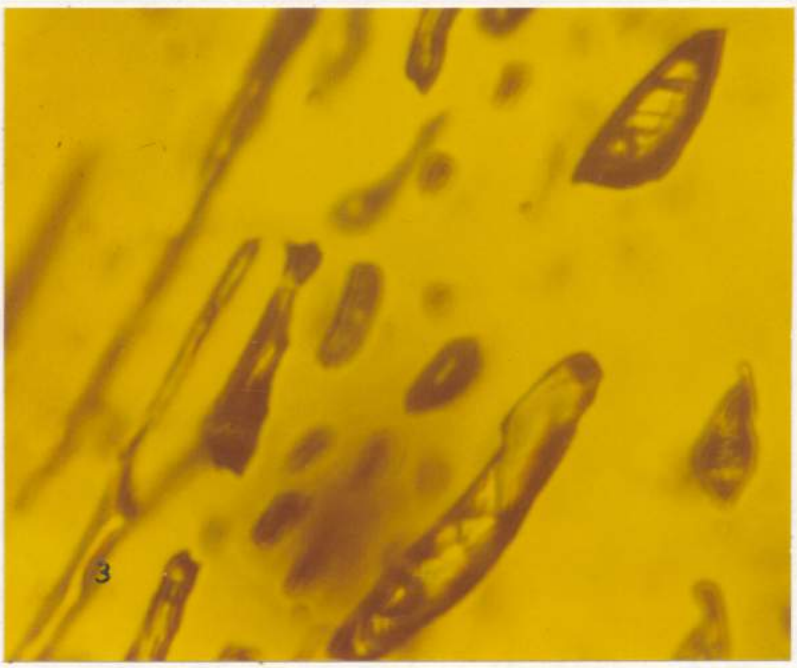


Plate 2

Figure 1. Large, isolated, moderate salinity inclusion in sphalerite: interpreted as primary.

Figure 2. Large, thin, flat, moderate salinity inclusion in sphalerite: interpreted as psuedosecondary.

Figure 3. Group of smaller, low salinity inclusions in sphalerite: interpreted as secondary.

Inclusions are magnified 500x.

flat inclusions of moderate salinity trapped along cleavage planes (Plate 2). They are interpreted as examples of ore forming fluid, present at some time during crystal genesis.

Primary and secondary inclusions in gangue minerals were difficult to distinguish. However, even primary inclusions in quartz and dolomite do not necessarily represent ore forming solutions since they are probably earlier formed phases.

INTERPRETATION OF FREEZING DATA

Direct chemical analyses, of fluids in inclusions indicate that Na, Ca, and K are generally the most abundant cations reported in the literature and Cl the dominant anion (Roedder, 1972).

The use of experimentally determined binary, ternary and quaternary phase diagrams containing the above components, along with observations of melting behavior of frozen inclusions, allows a qualitative and semi-quantitive estimate of the major components present in aqueous fluid inclusions. For example, as discussed in a previous section, in an aqueous inclusion the observed freezing point depression of ice provides an estimate of the total salinity. This is reported as equivalent weight % NaCl, obtained from the binary system NaCl-H_2O (Fig. 7), since many constituents of fluid inclusions have similar freezing point depressions.

If NaCl were the only salt dissolved in a fluid inclusion, then two melting events would be seen for fluids less saline than 23 wt.% NaCl: melting of hydrohalite ($NaCl \cdot 2H_2O$) at the eutectic, -20.8°C, and final melting of ice. Phase changes seen in the lower salinity inclusions of this study approximate the

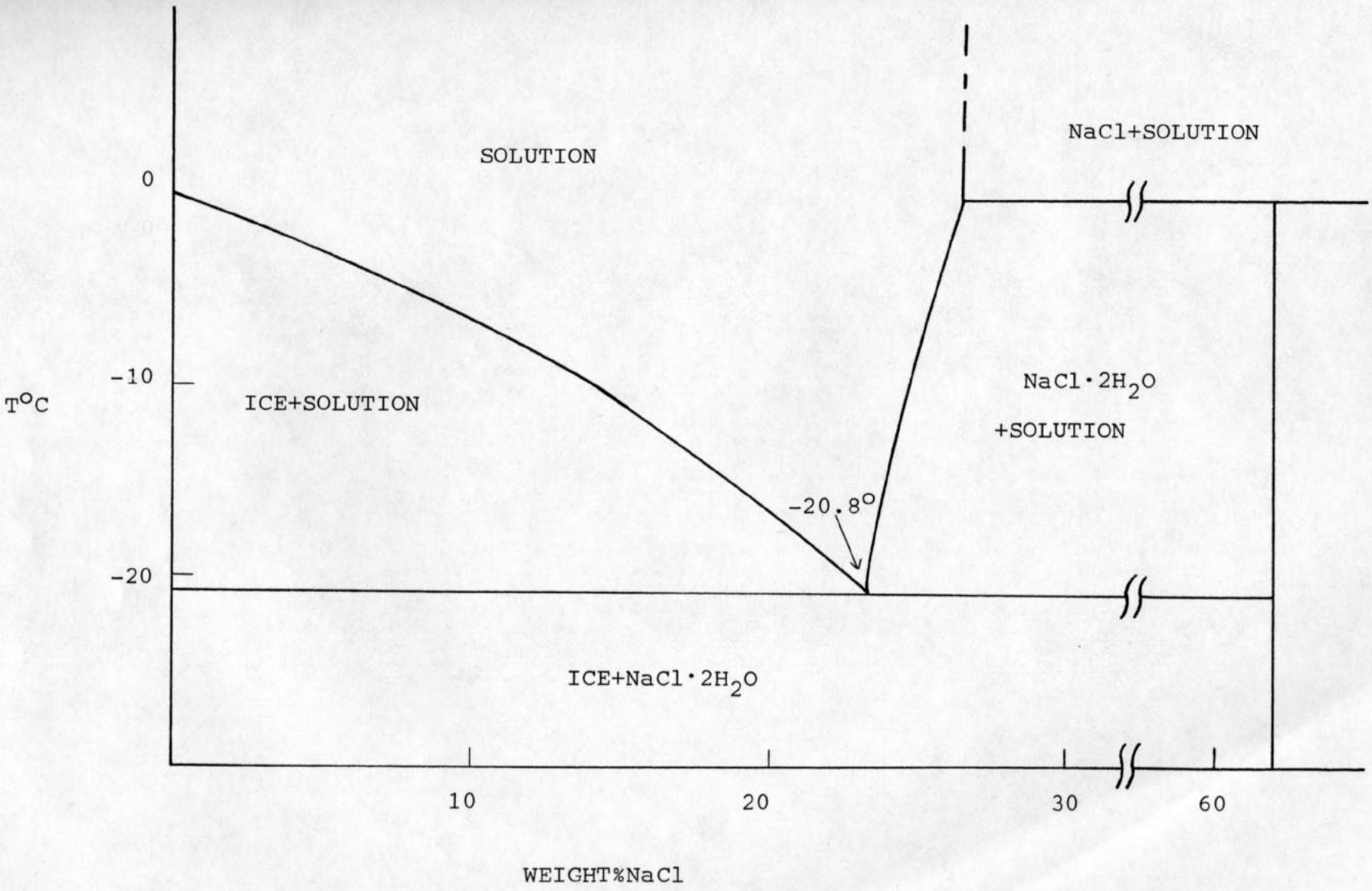


Figure 7. NaCl-H_2O system from Roedder (1963) and Potter et. al. (1977)

simple $NaCl-H_2O$ system. The first detectable melt is between -21.3° and -20.6° which is close to the eutectic in that system. When ice melts in the presence of vapor it is often between -5° and -1°C indicating salinities of 2 to 7 weight % NaCl. However, more often ice melts just below 0°C and the vapor bubble does not appear until higher temperatures.

Melting at temperatures lower than -20.8°C indicates the presence of other components in the fluid. Thus the melting data from the moderately saline fluid inclusions present in these samples suggest that other components, in addition to NaCl, are dissolved in the fluid. The addition of KCl to the $NaCl-H_2O$ system depresses the eutectic slightly from -20.8° to -22.9°C, which is difficult to detect in view of the small temperature change. In contrast, if $CaCl_2$ is added to the same system (Fig. 8), the eutectic is depressed to -52°C, a much more significant change. From freezing data obtained on the moderately saline inclusions of this study the presence of Ca is suggested by observation of first melting temperatures as low as -60°C.

In the $NaCl-CaCl_2-H_2O$ system, the number of melting events which should be observed in a frozen moderately saline inclusion increases to 3. In these samples 15

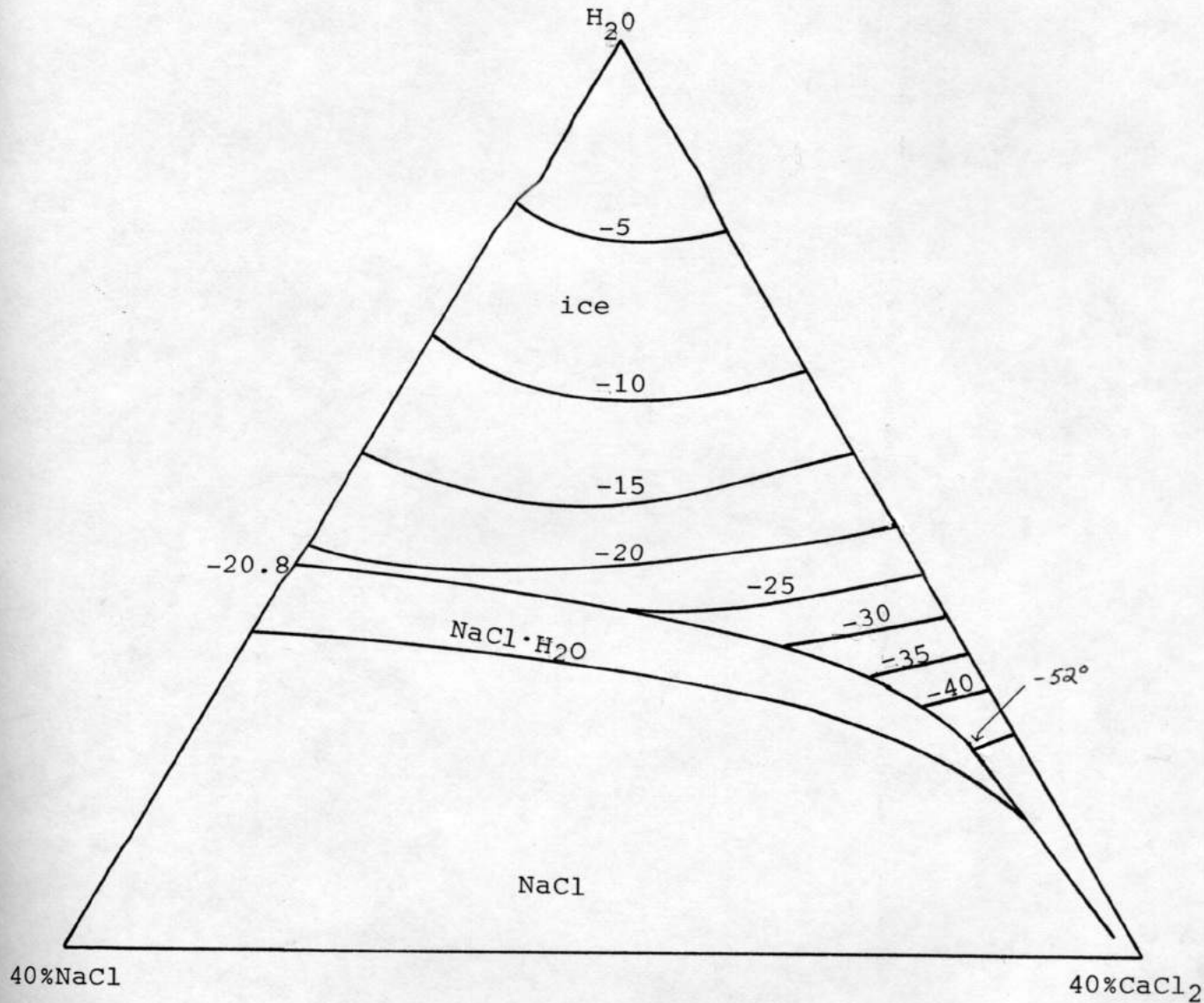


Figure 8. NaCl-CaCl-H_2O system from Yanatieva (1946)

wt. % salinity inclusions exhibit first melting possibly of $CaCl_2$-$6H_2O$ close to -52°C; this is followed by melting of the hydrohalite phase, and ice finally melts by -11°C. The melting point of hydrohalite depends upon the ratio of NaCl to $CaCl_2$ dissolved in the fluid. For example, the moderately saline inclusions in this study have hydrohalite melting points mostly between -21.3° and -22.9°C indicating that the composition of the salt in these inclusions is between 70 and 90 wt. % NaCl in the NaCl-$CaCl_2$-H_2O system (Fig. 8). The Na-rich character of the fluid is also suggested by the observation of very slight melting at low temperatures, close to the eutectic minimum, and the generation of a large amount of melt when hydrohalite melts.

A few moderate salinity inclusions in quartz and sphalerite behaved somewhat differently. First melting occurred by -50°C but by -35°C much melt was visible, suggesting the inclusions may be more Ca rich. Hydrohalite melted between -25° and -23° indicating that the salt dissolved in these inclusions is between 30 and 50 wt. % CaCl in the NaCl-$CaCl_2$-H_2O system.

Although most of the features of the melting behavior of these inclusions can be explained using the NaCl-$CaCl_2$-H_2O system, KCl is a common constituent

of fluid inclusions. Therefore the quaternary diagram ($NaCl-CaCl_2-KCl-H_20$) probably applies to these samples (Fig. 9). In this system, the eutectic minimum is approximately -56°C (Konnerup-Madsen, 1976) and with the addition of a component, 4 melting events should be observed upon warming a moderately saline frozen inclusion. In the primary inclusions of this study first melting was observed at temperatures as low as -60°C. -54°C was the most common temperature at which melting was first observed. This supports the suggestion that perhaps small amounts of KCl or another component are present in the fluid. However, the presence of small amounts of KCl do not significantly alter the $CaCl_2-NaCl-H_20$ phase equilibria because temperature shifts are small (Fig 8,9) and probably difficult to detect. Usually between first observed melt and the disappearance of hydrohalite some gradual melting occurs which cannot be attributed to melting of any specific phases. However, sometimes, rapid melting occurs at approximately -35°C and this could represent melting of a phase in a more complex system (Crawford et al., 1979).

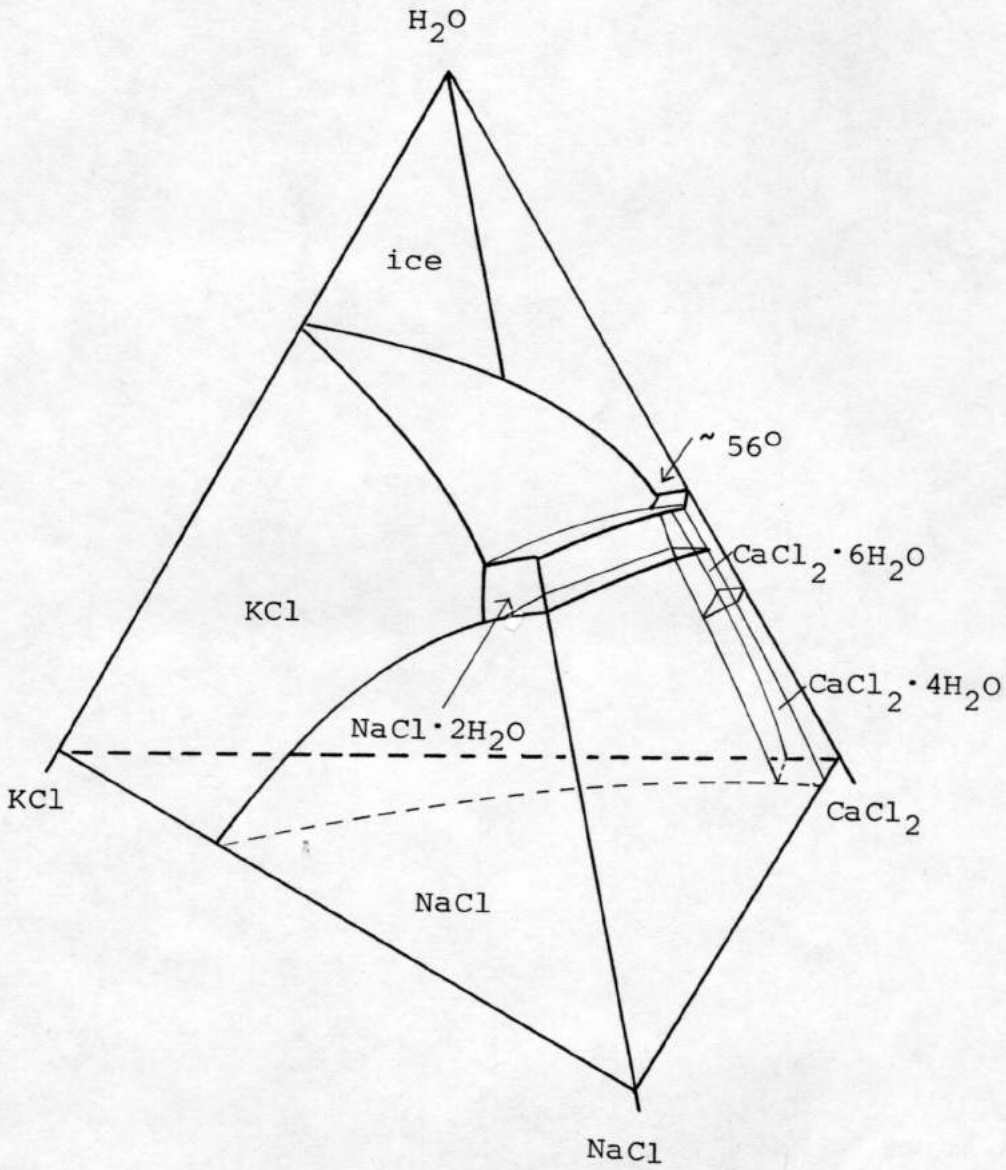


Figure 9. A partly schematic polythermal projection of the water rich part of the NaCl-CaCl-KCl-H_2O system. The phase relations cover a temperature range from about +100° at the base of the tetrahedron down to a temperature of the quaternary eutectic point of approximately -56°C. (Konnerup-Madsen, 1979).

INTERPRETATION OF HEATING DATA

Experimental precautions

During the course of the low temperature investigation it became apparent that two very different fluids were trapped in the minerals studied. One is a moderate salinity (10-16 wt. % NaCl) brine, and the other a more dilute (0-7 wt. % NaCl) solution. After all freezing phenomena were observed, homogenization temperatures for the same inclusions were determined. In the moderate brine inclusions all the Th values clustered around 145° at New Galena, 155° at Audubon and 175° at Phoenixville. In the more dilute inclusions, distribution of Th was much more erratic and ranged from 119°.0 to 168°.4C. Possible explanations for the scatter include: 1) some inclusions could have auto-decrepitated before sampling; 2) some inclusions could have leaked during freezing runs; 3) the inclusions had "stretched" during low temperature runs; 4) they could have been trapped over a range of conditions.

The first two explanations do not seem likely as autodecrepitation and leaking usually results in an obviously bigger vapor bubble and this change was not seen. The third possibility seemed most likely because all these inclusions had been frozen before heating and "stretching" can occur when an inclusion with a small vapor bubble is frozen because of the expansion of ice upon freezing

(Roedder,1980). If stretching could not be proved, however, trapping over a range of condition would be indicated.

In order to determine whether "stretching" had occurred three samples were studied which had never been frozen. Homogenization temperatures of a number of inclusions in each sample were determined and they were then frozen to determine their salinities. Both moderate and low salinity inclusions were observed. The same inclusions were then reheated to determine if there had been an increase in Th. None of the moderate salinity inclusions homogenized at higher temperatures, but the Th of some of the low salinity inclusions increased slightly (Table 1b). After freezing a second time, the Th in some low salinity inclusions increased significantly (Table 1b) as shown by an increase in the size of the vapor bubble (Plate 3) as well as a greater increase in Th. Apparently, among the low salinity inclusions, certain ones hardly stretch and others stretch significantly upon freezing. Detecting stretching by noting an increase in the size of the vapor bubble, may be difficult, because the change can be small.

The main reason for stretching in these inclusions is the expansion of water upon freezing to completely fill the inclusion cavity. If the inclusion contains a large vapor bubble it can accommodate the expanded

STRETCHING DATA

Table 1a. Data from low salinity inclusions frozen prior to heating.

SAMPLE	INCLUSION	Th	# FREEZING RUNS
Zn-83	B-1	137.9°	5
"	B-4	141.5°	5
"	B-5	142.6°	7
Zn-43	A-1	130.3°	2
"	B-1	123.4°	2
C	A-1	168.4°	4
H	F-1	119.0°	1
K	B-1	133.7°	2
G	B-1	151.1°	4
H	D-1	143.0°	1
"	A-1	154.6°*	1

*, possibly necked down.

Table 1b. Data from low salinity inclusions heated prior to freezing.

SAMPLE	INCLUSION	Th_1	Th_2	Th_3
M	E-1	110.4°	n.c.	n.d.
"	E-3	115.2°	119.4°	127.5°
A	C-1	113.8°	n.c.	n.c.
"	C-2	109.7°	113.7°	138.9°
H	H-1	126.1°	leaked	n.d.
"	G-1	116.6°	123.0°	n.d.

n.c. no change

n.d. not determined

Th_1 sample never frozen

Th_2 sample frozen once

Th_3 sample frozen twice

Plate 3

Figure 1. Low salinity inclusion which has never been frozen(Th=118°).

Figure 2. Same inclusion after freezing once (Th=122°).

Figure 3. Same inclusion after freezing twice (Th=138°).

Magnification 500x.

volume of ice upon freezing. But, if the vapor bubble is small, it is eliminated during the expansion of ice and the resulting pressure may cause the walls of the inclusion to stretch. Low salinity inclusions may be more likely to show this phenomenon because they contain more water then high salinity fluids hence more ice forms upon freezing and more expansion occurs, per unit volume of fluid.

T,P. Conditions for Ore Formation

The homogenization temperature (Th) is the temperature at which the vapor bubble in a fluid inclusion disappears on heating (Roedder,1976). A fluid can be trapped as an inclusion anywhere in P-T space. Once a homogeneous fluid is trapped, since fluid inclusions are closed systems, the density of the fluid is fixed. Thus, on cooling, the P-T path for the fluid is constrained to follow a constant density path (isochore) for the particular fluid (Fig. 10). As the inclusion cools a vapor bubble forms when the boiling curve is reached. On the heating stage the process is reversed and the temperature conditions along the boiling curve are reproduced. Thus the homogenization temperature is the minimum trapping temperature, if a homogeneous fluid was trapped. If the fluid was trapped at conditions away from the boiling curve, a pressure correction must be applied to the homogenization temperature to determine the trapping temperature (Roedder and Bodnar, 1980). The pressure correction is a function of fluid composition because dissolved salts affect the compressibility of fluids and thus affect the isochores. If trapping pressure, composition and Th are known then temperature of formation (Tf) can be determined. By the same reasoning, if temperature conditions of formation were known, along with composition and Th, the pressure conditions for formation

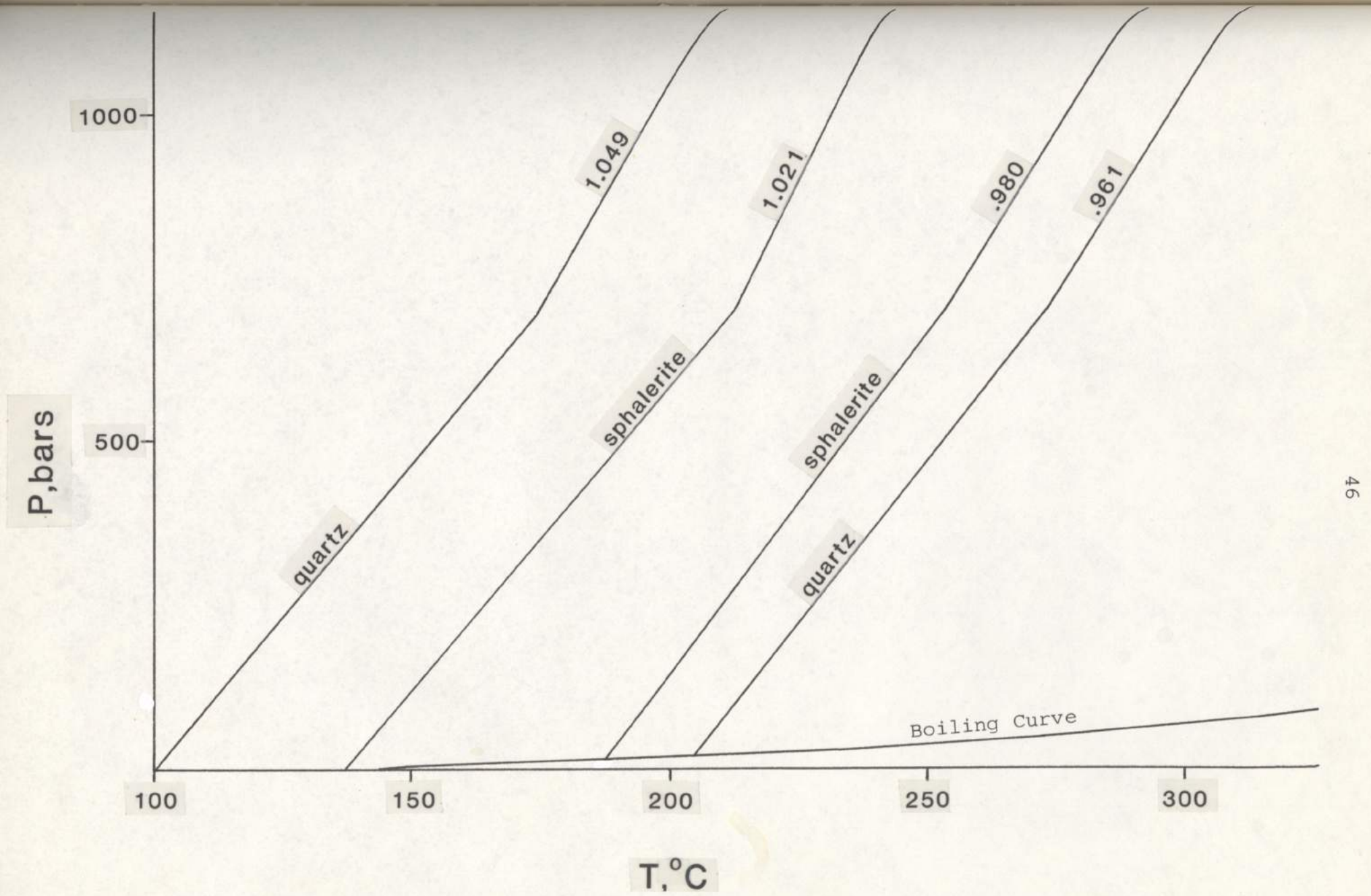


Figure 10. Pressure-temperature-density diagram for fluid composition 13 equivalent wt.% NaCl. (Potter and Brown, 1977) and (Haas, 1976). Isochores correspond to range of T_h in Sphalerite and quartz.

could be inferred.

Pressure at the time of entrapment of the inclusions is usually difficult to calculate. First, the depth below the surface at the time of trapping must be estimated from geologic evidence. Secondly, it is not known whether lithostatic or hydrostatic pressure prevailed during trapping. Roedder and Bodnar (1980) contend that pressures in many natural situations are probably somewhere between lithostatic and hydrostatic.

For this investigation both lithostatic and hydrostatic pressures were calculated for each deposit (Table 2). The depth of emplacement of the New Galena and Audubon ores were estimated from observations by Smith (1977) on the location of the ore in the Triassic stratigraphic section and from paleothickness in the basin estimated by Glaeser (1966) and Bascom and Stose (1938). The Phoenixville deposits were treated as though they formed at the same depth as the Audubon ore since they are only 4 km from Audubon. It is assumed that the ore was deposited once the basin was full and before substantial erosion took place. This is based partly on the fact that ore bearing veins cut Triassic dikes which are thought to have been emplaced near the end of basin filling. According to Miller (1924) some ore has

Table 2. Data and results of calculations to determine estimated pressure conditions for deposition of New Galena, Audubon and Phoenixville ores.

New Galena:

overburden-approximately 3000m

sandstone, shale, conglomerate

average density=2.2 gm/cm^3

lithostatic pressure = .65 Kb

hydrostatic pressure = .30 Kb

Audubon:

overburden-approximately 4100m

sandstone, shale, conglomerate

average density = 2.2 gm/cm^3

lithostatic pressure = .9 Kb

hydrostatic pressure = .4 Kb

Phoenixville:

assumed same as Audubon

been deformed after deposition, so it was emplaced before the last movement on faults which probably occurred while the basin was full. A second assumption is that the whole basin was uniformly filled by the entire known stratigraphic sequence. To my knowledge, there is no information on the exact thickness of sediment deposited on the southeast side of the basin. As a result the Audubon and Phoenixville pressure estimates may be too high especially since the Phoenixville area is outside the present confines of the basin. The estimated pressure for New Galena is probably the most accurate since the maximum thickness of Triassic rocks in the central portion of the basin is well documented (Glaeser, 1966; Van Houten, 1969).

Converting Th to Tf

The technique for converting Th to Tf involves three variables: fluid density, composition, and estimated pressure conditions for entrapment. Using the data of Potter and Brown (1977) and Haas (1976) P-T-density diagrams were constructed for the compositions of interest. Figure 10 shows the isochores which correspond to the range of homogenization temperatures of 13 wt. % NaCl equivalent inclusions in sphalerite and quartz. It is read by finding the homogenization temperature observed experimentally along the boiling curve at the bottom of the graph (Fig. 10). The isochore originating at this point is followed up until it crosses the estimated pressure conditions read from the ordinate and true formation temperature is then read from the abcissa. Similarly, the true formation pressure can be determined if the other two variables are known.

This technique was employed on the moderately saline, primary inclusions, in ferroan dolomite, quartz, and sphalerite in order to determine the probable formation temperature of the host minerals. The results for both estimated lithostatic and hydrostatic pressure conditions, are reported in Table 3.

Table 3. Formation temperature (Tf) for inclusions under estimated lithostatic (L) and hydrostatic (H) pressure.

NEW GALENA

HOST	Th (range)	SALINITY	d (range)	P	Tf (range)
sphalerite	135°-180°	11%	1.002-.955	L	213°-243°
"	"	"	"	H	170°-210°
"	139°-163°	15%	1.040-1.017	L	203°-230°
"	"	"	"	H	165°-187°
Fe Dol	177.1°	13%	.994	L	235°
"	"	"	"	H	200°

AUDUBON

HOST	Th (range)	SALINITY	d (range)	P	Tf (range)
sphalerite	145°-161°	11%	.998-.885	L	233°-256°
"	"	"	"	H	187°-203°
"	138°-174°	13%	1.021-.987	L	227°-263°
"	"	"	"	H	177°-217°
quartz	123°-205°	11%	1.014-.943	L	200°-287°
"	"	"	"	H	167°-216°
"	101°-207°	13%	1.049-.961	L	187°-285°
"	"	"	"	H	143°-243°
"	200°	15%	.984	L	285°
"	"	"	"	H	235°

PHOENIXVILLE

HOST	Th (range)	SALINITY	d (range)	P	Tf (range)
sphalerite	130°-177°	11%	1.007-.972	L	225°-267°
"	"	"	"	H	175°-223°
"	169°-188°	13%	.994-.980	L	245°-270°
"	"	"	"	H	210°-225°
"	179°	15%	1.002	L	263°
"	"	"	"	H	220°
Fe dol	172°	13%	.989	L	263°
"	"	"	"	H	218°

DISCUSSION OF RESULTS

The primary ore fluid, suggested by freezing data, is a complex brine which contains NaCl as the major dissolved solid, Ca is present in smaller amounts and other cations such as K, Mg, Fe may be present. Salinity ranges from 10-16 equivalent weight % NaCl and the density of the fluid ranges from 1.040 to 0.955.

New Galena samples have the most saline inclusions (16%) but also contain an equal amount of 11 wt. % inclusions. Phoenixville and Audubon samples mainly contain inclusions between 11-14 wt. % NaCl. Possibly the higher salinity brine present in New Galena sphalerite represents interaction of the hydrothermal fluid with the wall rock as it migrated through fractures in the saline Lockatong formation. The ore fluid reacting with Stockton siltstone and Precambrain crystalline rocks might not be as saline. The range of salinity both between deposits and within the deposit could result from blind sampling.

Roedder (1974) has demonstrated that discrete zones in sphalerite crystals can have very different salinity and Th values which represent changes in the ore solution with time. It should be pointed out that fluid inclusions from all three color variations

yellow, gold and orange, in sphalerite were purposely examined in this study in order to determine whether the color change represents a variation in ore forming solution. From the data shown in Appendices A, B, C it can be seen that there is no obvious correlation between color zone and salinity or Th.

The temperature of the trapped fluids in sphalerite, determined from density, composition and estimated pressure ranged from 203°C to 270°C, if lithostatic pressure is assumed, and 165° to 225°C, if hydrostatic pressure is assumed. Audubon and Phoenixville inclusions apparently formed at slightly higher temperatures then New Galena inclusions. This may reflect innaccuracies in pressure estimates rather than true temperature differences. Pressure on the fluids trapped in sphalerite from New Galena range from .3 hydrostatic to .65 kb lithostatic based on burial depth. According to Roedder (1980) most ore solutions are probably under pressure conditions somewhere between lithostatic and hydrostatic hence these deposits may have formed at temperatures near 200°C and pressures around .4 kb.

The lower salinity, secondary inclusions, which exhibited metastable melting behavior, formed at lower temperatures. Because there is no evidence on which to base an estimate of pressure or temperature conditions

for formation, no homogenization temperature corrections can be made. However,there is a decrease in Th and salinity which could represent a waning of heat and changes in the fluid. These fluid inclusions could also represent ground water trapped at a much later time.

There apparently are two types of inclusions present in gangue minerals, one deposited at higher temperature than ore forming fluid and ore deposited at a lower temperature. Only high temperature, moderately saline brine was found in ferroan dolomite and both gangue minerals appear to be early formed minerals. So perhaps the higher temperature inclusions represent early fluids responsible for gangue mineral formation.

MODEL FOR ORE FORMATION

In order to postulate a model for the formation of these deposits a brief discussion of fluid inclusion data from Mississippi Valley-type (MVT) and magmatic related, base metal, deposits is desirable in order to compare with data obtained from these Zn-Pb-Cu deposits. Fluid inclusions in MVT deposits have densities close to or slightly greater than 1.0, have high Na contents and have salinities seldom below 15 wt. % NaCl equivalent and often greater than 20 wt. % NaCl equivalent (Roedder, 1976). Inclusions of methane and hydrocarbons and formation temperatures between 100° and 150°C further characterize MVT deposits. In contrast, inclusions from shallow, intrusive related, base metal vein deposits have salinities between .5% and 12 wt. % NaCl and densities significantly less than 1.0 (Roedder, 1976). Organic matter is never present and temperatures of formation are between 200° and 330°C (Spooner, 1981).

From the data collected in this study, these deposits are not clearly similar to either MVT or magmatic-vein deposits. However, some characteristics of the ore fluid are quite similar to MVT ore solutions. These include the Na rich nature of the brine and densities which are closer to 1. In addition, certain

geologic relationships are similar such as, occurrence in and on the margin of a sedimentary basin, similar mineralogy, and ability of ore solution to replace carbonate (Ohle, 1980). This suggests that the fluids which deposited the Phoenixville, Audubon and New Galena ores may have an origin similar to MVT fluids: Formation by expulsion of dense metalliferous brines which migrate from sedimentary basins into fractures and breccias in host rocks. The somewhat higher Tf and lower salinity for these ore fluids when compared to typical MVT solutions must be explained by the proposed model.

The source of the metals in the brines could have been the thick sedimentary pile in the Newark basin. Red beds, especially sandy, permeable red beds, have relatively high metal contents associated with carbonate and hematite cement (Ohle, 1980). Black shales also contain high metal contents and arkoses may have lead subsitituted in feldspars (Hanor, 1979), Helgeson (1969) has demonstrated that these metals may be mobilized as chloride complexes by hot saline water. The solubility of sphalerite in aqueous chloride-sulfide solutions increases as temperature rises and pH falls (Melent'yev et al., 1969). Hinners and Holland (1963) have shown

that sphalerite solubility also increases with sodium chloride concentration. Fluid inclusion data from these deposits indicate a moderately saline brine at 200°C which is clearly capable of carrying metals in solution.

The saline water could possibly originate by circulation of fluid through fracture systems in the Lockatong formation. Some beds of the Lockatong formation contain casts of glauberite ($Na_2Ca(SO_4)_2$) and/or gypsum ($CaSO_4$) replaced by analcime ($NaAlSi_2O_6$) (Van Houten, 1969). Hot water circulating through these beds could dissolve glauberite and gypsum forming a dense $Na-Ca-Cl-SO_4$ brine. Perhaps the reason these brines are less saline then typical MVT brines is because they originate in a non-marine basin in contrast to the marine sedimentary basin of the MVT deposits.

A heat source is needed to generate the hot solutions. Geothermal gradients in explored deep sedimentary basins are usually between 15-40°C/km so depths between 5-13 km are needed to attain temperatures on the order 200°C (Hanor, 1979). Since the maximum estimated thickness of sediments in the Newark basin is 6000 m, the geothermal gradient would have to be fairly high if solutions of $\geq$ 200°C are to be generated. Axial rift zones such as the Red Sea are known to be areas of high heat flow (Ellis, 1979). Since the Newark Basin is

thought to have formed next to an incipient rift zone, it is possible that the geothermal gradient was abnormally high and caused a circulating hydrothermal system within the basin.

Careful petrographic examination of Newark Group sediments and volcanics confirms that they have been metamorphosed. The occurrence of prehnite and other zeolites in the sedimentary and igneous rocks of the Newark Basin is well documented (Schaller, 1932). Van Houten (1962) has described the analcime rich sediments of the Lockatong formation and has observed the conversion of analcime to albite with increasing depth of burial. It is clear that the metamorphism of the rocks has occurred in either the zeolite or prehnite-pumpellyite facies of regional metamorphism, which means the rocks have attained temperatures on the order of 200°C, at some time subsequent to deposition. Evidently, the temperatures within the Newark Basin were high enough to produce the solutions which were trapped as moderately saline fluid inclusions in sphalerite. Therefore, a deep seated igneous body, which has been postulated for deposition of the ore need not be invoked to explain the origin of the hydrothermal solutions.

ORE DEPOSITION

A number of factors have been postulated for the deposition of ore in hydrothermal systems. These include mixing of two different solutions, pressure changes, temperature variation, and chemical reactions between moving solution and the rocks lining channelways (Skinner, 1979). The fluid inclusion data collected for these deposits suggest that the first two factors do not seem to have played an important role in the development of these ores. Boiling of fluids at shallow depths is a common result of rapid pressure release but there is no indication that boiling occurred in the veins of southeastern Pennsylvania. If fluid mixing were a factor in ore deposition then fluid inclusions of different compositions but similar temperatures of formation should occur. But there is no fluid inclusion evidence that two fluids were present at the same time.

Some data suggest chemical reactions with wallrocks and/or temperature variation may have resulted in ore deposition. The ore was deposited in three different host rocks as previously discussed. Since copper ore predominates at Audubon where the wall rock is sandstone, some type of wall rock reaction could have aided the precipitation of copper. In addition, wallrock alteration

is prevalent at the Audubon and Phoenixville deposits and replacement features are present in the New Galena breccia. The fact the Pb sulfides are concentrated at New Galena and Phoenixville may suggest that the two host rocks have a common feature. It seems, the Lockatong shale and Precambrian crystalline rocks are both pyrite rich, while the Stockton siltstone does not contain appreciable pyrite. Perhaps this affected the solubility of Pb in the ore solutions. However, it is also possible that differences inherent to the ore forming fluid resulted in the predominance of galena or chalcopyrite at different localities. Ore solutions depositing Pb sulfides could have a Pb-rich source and fluid depositing Cu sulfides a Cu-rich one.

Formation temperatures inferred from the fluid inclusions of all three deposits are similar which suggests some control of temperature on ore depositions. However, the solubility of galena and sphalerite in aqueous chloride solutions is high (Melent'yev et al., 1969; Helgeson, 1969), so temperature decrease alone did not cause sulfide precipitation. The combined effects of chemical reactions with wallrocks and temperature variation may have controlled ore formation, but more geological data is needed to document more exactly the factors affecting ore deposition.

AGE OF MINERALIZATION

Some of the ore filled fractures in Precambrian rocks cut Triassic diabase dikes placing a lower limit on time of deposition. Miller (1924) states that the shattered character of the gangue and ore minerals and the presence of clay gouge indicates there has been some displacement following the formation of the ore. Therefore, the ore probably formed after most igneous activity had occurred but before tectonic activity had ceased, possibly during the Lower Jurassic period of basin rifting, tilting and warping.

SUMMARY

The Audubon, New Galena, and Phoenixville base metal vein deposits were deposited by hydrothermal solutions in northeast trending faults and fractures in three very different host rocks, the Stockton sandstone, the Lockatong shale and Precambrian crystalline rocks respectively. The fractures and faults are probably related to tensional stress developed by incipient rifting associated with the opening of modern day Atlantic Ocean.

The ore-forming hydrothermal fluid has been investigated by microthermometric analysis of fluid inclusions in sphalerite, quartz and dolomite. The results obtained by microthermometry on primary or pseudosecondary inclusions in sphalerite indicate that the ore was deposited by a complex sodium-rich brine of moderate (11-16 equivalent wt. % NaCl) salinity at temperatures probably around 200°C. Local fluid-wallrock interaction may have produced the higher salinity fluids present at the New Galena deposit.

Inclusions in gangue minerals have salinities that range between 11-15 % but have two temperatures of deposition, one higher (250°) than the ore forming fluid and one lower (150°) than the ore forming fluid.

Secondary inclusions in sphalerite have lower salinity, commonly exhibit metastable melting behavior, and may also have lower temperatures of formation. It is clear, from fluid inclusion evidence, that the ore forming fluids changed character and evolved with time.

The Na-rich character of the fluid suggests that dissolved constituents in the fluids were derived from the Na-rich sedimentary rocks of the Newark Basin. High heat flow in the Triassic-Jurassic axial rift zone possibly caused an anomalously high geothermal gradient in the basin which led to the mobilization of connate, metal rich, brines which migrated through faults and fractures. Deposition of ore occurred where temperature and chemical conditions developed through wall rock interaction with the fluid, which favored sulfide precipitation.

The data obtained in this investigation suggests that the ore solution is similar in density and composition to fluids which deposit MVT base-metal ores but differences in salinity and higher formation temperatures are evident. The slightly lower salinity and higher formation temperature, are consistent with a fluid mobilized in a nonmarine sedimentary basin with an

anomalously high geothermal gradient.

SUGGESTIONS FOR FUTURE WORK

The nature of an investigation of this type is such that it often creates as many puzzles as it solves. Future work could be aimed at determining the fossil geothermal gradient in the Newark Basin. A fluid inclusion study of quartz cement in the various Triassic sedimentary rocks could provide valuable data on temperatures attained in the sedimentary pile, and hence either support or disprove the model of hydrothermal solutions originating as mobilized connate brines.

Trace element analysis of both host rock and ore would certainly provide further evidence on the source of the hydrothermal fluids. In addition, trace elements could shed some light on the importance of wallrock reactions on deposition of the ore.

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Appendix A. Fluid Inclusion Data from New Galena District.

SAMPLE	INCLUSION	HOST(color)	SIZE	Te	Tm (hydrate)	Tm (ice)	Th L-V
M	A-1	yellow sph	.1 mm	-45°	-21.3°	-8.1°	137.8°
"	A-2	"	"	-38°	-20.9°	-5.7°+	134.6°*
"	A-3	"	.01 mm	-45°	-21.3°	-8.1°	143.6°
"	A-4	"	"	"	"	"	149.8°
"	A-5	"	"	"	"	"	135.5°
"	A-6	"	n.d.	-54°	-21.3°	-7.8°	152.6°
"	A-8	"	n.d.	"	"	"	159.2°
"	A-10	"	n.d.	-54°	-22.4°	-11.0°	145.2°
"	A-11	"	n.d.	"	"	"	154.0°
"	A-12	"	n.d.	"	"	"	157.7°
"	B-1	orange sph	.01 mm	-50°	-22.9°	-10.5°	163.7°
"	B-2	"	"	"	"	"	153±3°
"	C-1	gold sph	.02 mm	"	-23.0°	-11.1°	144.6°
"	D-1	Fe dol	n.d.	-52°	-21.9°	-9.2°	171.6°
K	A-1	yellow sph	.01 mm	-55.3°	-22.4°	-9.0°	n.d.
"	B-1	"	.02 mm	-25.2°	n.d.	-4.3°	133.7°*
L	A-1	gold sph	.1 mm	-57°	-22.4°	-11.4°	140.0°
"	A-2	"	"	-58°	-22.8°	-11.8°	139.8°
"	A-3	"	"	"	"	"	138.8°
Zn-28	B-1	orange sph	n.d.	-53°	-22.4°	-10.0°	138.6°
"	D-1	gold sph	n.d.	-60°	-22.4°	-7.8°	139.8°
M	E-1	yellow sph	.01 mm	n.d.	n.d.	-.5°+	115.2°
"	E-3	"	n.d.	n.d.	n.d.	-.5°+	110.4°
"	F 1	"	n.d.	n.d.	-22.4°	-7.8°	159.2°
"	Fb-1	"	n.d.	n.d.	"	"	180.8

Appendix B. Fluid Inclusion Data from Audubon District

SAMPLE	INCLUSION	HOST (color)	SIZE	Te	Tm (hydrate)	Tm (ice)	Th L-V
H	A-1	gold sph	.01mm	n.d.	-20.8°	-1.0°+	129.8°*
"	D-1	orange sph	.02mm	n.d.	n.d.	-.8°+	143±3°*
"	E-1	yellow sph	n.d.	-52°	-22.5°	-9.0°	158.2°
"	F-1	"	n.d.	n.d.	-22.4°	-1.4°+	119.0°*
"	G-1	"	n.d.	n.d.	n.d.	-2.8°	116.6°
"	H-1	gold sph	n.d.	-51°	-21.4°	-4.6°	126.1°
A	A-1	yellow sph	n.d.	n.d.	-22.9°	-8.8°	174.0°
"	B-1	gold sph	1mm	-42°	-22.7°	-8.7°	166.1°
"	C-1	yellow sph	.01mm	n.d.	n.d.	-2.8°+	113.8°
"	C-2	"	n.d.	n.d.	n.d.	"	109.7°
"	D-1	gold sph	.01mm	-44°	-21.7°	-8.8°	163.0°
G	A-1	yellow sph	n.d.	-57°	-22.1°	-7.4°	159.6°
"	B-1	gold sph	.02mm	n.d.	n.d.	-3.6°	151.1°*
"	B-2	orange sph	"	-54°	-21.9°	-7.8°	161.3°
"	B-4	gold sph	"	-60°	-21.4°	-7.5°	160±3°
Zn-83	A-1	gold sph	n.d.	-22°	-22°	-1.5°+	n.d.
"	A-2	"	.05mm	-52°	n.d.	-8.8°	137.9°
"	A-3	"	.1mm	"	-22.8°	-9.0°	156.8°
"	B-1	yellow sph	.05mm	-20,8°	-20.8°	n.d.	137.9°*
"	B-4	"	.01mm	n.d.	-22.0°	-1.2°+	141.5°*
"	D-1	gold sph	n.d.	-50°	-21.9°	-7.1°	145.2°
"	D-2	"	n.d.	"	"	"	145.1°
"	D-3	"	n.d.	-54°	-22.3°	"	145.0°
"	B-2	"	n.d.	-33°	-21.1°	-8.2°	162.3°
"	B-3	"	n.d.	"	-21.9°	-9.1°	163.9°
"	G-1	"	n.d.	-56°	-21.9°	-8.7°	165.9°
"	G-2	"	n.d.	-54°	"	-8.8°	"

Appendix B. continued,

SAMPLE	INCLUSION	HOST (color)	SIZE	Te	Tm (hydrate)	Tm (ice)	Th L-V
Zn-83	D-4	clear quartz	.01mm	-57°	-22.8°	-8.2°	162.8°
"	D-5	"	"	"	"	"	141.2°
"	D-6	"	"	"	"	"	"
"	D-7	"	"	"	"	"	"
"	D-8	"	.02mm	-52°	-22.4°	-8.6°	192.0°
"	D-9	"	"	-47°	-22°	-8.5°	178.8°
"	D-10	"	"	-52°	n.d.	-7.9°	100.6°
"	D-11	"	"	-56°	n.d.	-7.6°	123.4°
"	C-1	"	n.d.	n.d.	-21.9°	-7.4°	205.3°
"	C-2	"	n.d.	n.d.	-22.4°	-10.7°	200±5°
"	C-3	"	n.d.	n.d.	"	-8.3°	207.3°
"	C-4	"	n.d.	n.d.	-22.1°	-7.3°	200.1°
"	D-12	"	n.d.	-59°	-22°	-8.2°	175.8°
"	C-5	"	n.d.	-47°	-26°	-7.4°	121±5°
H	C-1	"	.01mm	n.d.	-21.7°	-9.4°	122.7°

Appendix C. Fluid Inclusion Data from Phoenixville District.

SAMPLE	INCLUSION	HOST (color)	SIZE	Te	Tm (hydrate)	Tm (ice)	Th L-V
C	A-1	orange sph	n.d.	n.d.	-20.6°	-5.1°	168.4°*
"	B-1	yellow sph	n.d.	-40°	-22.9°	-9.4°	183.2°
"	C-1	clear quartz	n.d.	-30°	-22.6°	-3.6°+	161.9°*
Zn-43	A-1	gold sph	n.d.	n.d.	-20°	-4.5°+	130.3°
"	B-1	yellow sph	n.d.	n.d.	-20°	-.7°+	123.4°*
J	A-1	yellow sph	.02mm	-50°	-21.9°	-6.8°	129.7°
N	A-1	gold sph	n.d.	-32°	-21.4°	-7.3°	168.8°
"	B-1	yellow sph	n.d.	-42°	-20.8°@	-7.2°	177.3°
"	B-2	"	n.d.	"	-21.7°	-7.5°	"
D	A-1	orange sph	n.d.	-54°	-24.9°	-11.8°	179.2°
"	B-1	yellow sph	n.d.	-57°	-23.9°	-5.8°	145±3°
"	B-2	gold sph	n.d.	-55°	-24.5°	-7.3°	145.8°
"	D-1	yellow sph	n.d.	-56°	-24.1°	-9.2°	169.5°
"	D-2	"	n.d.	"	"	-9.6°	175.7°
B	B-1	gold sph	n.d.	-56.9°	-22.6°	-9.3°	181.5°
"	D-1	"	n.d.	-54°	-22.0°	-9.6°	187.8°
"	D-2	orange sph	n.d.	"	-22.1°	-10.1°	187.9°
"	E-3	Fe dol	n.d.	-54°	-22.4°	-9.9°	177.1°

+, ice melted before return of vapor phase

*, may be anomolously high due to stretching of the walls of the inclusion

n.d. not determined

Accuracy of Tm, Th, ± .2°C except where otherwise noted.

All reported temperatures are corrected according to the calibration curve.